High magnetic susceptibility produced in high velocity frictional tests on core samples from the Chelungpu fault in Taiwan

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Abstract

We carried out high-velocity frictional tests on crushed fault gouge from core samples from Hole B of the Taiwan Chelungpu-fault Drilling Project to investigate the cause of high magnetic susceptibilities in the fault core. Black ultracataclasite resembling that observed in Hole B formed during the experiments, even under low axial stress of 0.5 to 1.5 MPa. The bulk magnetic susceptibility of the tested samples was proportional to the frictional work applied and increased as slip increased. Thermomagnetic analysis of the samples before frictional testing revealed that magnetization increased at temperatures above 400 °C, probably because of thermal decomposition of paramagnetic minerals. Both the thermally and mechanically induced formation of ferrimagnetic minerals by high velocity friction might have caused a magnetic susceptibility anomaly. Our experimental results support the assumption that heat generation of short duration, even if it is below the melting point, can increase magnetic susceptibility.

1. Introduction

The Taiwan Chelungpu-fault Drilling Project (TCDP) started in 2002 to investigate a unique slip behavior of the 1999 Chi-Chi earthquake (M_w 7.6) [*Ma et al.*, 2003]. Two boreholes (total depth, 2003.0 m in Hole A; 1352.6 m in Hole B), near the town of Dakeng in the northern part of the rupture zone [Kano et al. 2006], were drilled to penetrate the Chelungpu fault. In Hole B, three fault zones of the Chelungpu fault system, 1136mFZ (1134–1137 m), 1194mFZ (1194–1197 m), and 1243mFZ (1242–1244 m), were identified within the Pliocene Chinshui Shale, which consists predominantly of weakly bioturbated siltstone [Hirono et al., 2006a]. Hirono et al. [2006b] conducted a detailed analysis of core samples from the fault zones in Hole B and reported that cohesive dark material (BM disc) was formed within fault zones. The BM disc was identified under microscopic examination as pseudotachylyte. However, the proportion of the melt material appeared to be small, suggesting that frictional melting is not the main mechanism that controlled slip behavior during the Chi-Chi earthquake. Furthermore, the BM disc had high magnetic susceptibility and low inorganic carbon content. The high magnetic susceptibility might have resulted from the formation of magnetic minerals from paramagnetic minerals [Mishima et al., 2006] within the BM disc that were subjected to temperatures of at least 400 °C. Bulk magnetic susceptibility is easily measured and might be an indicator of heat generation during seismic slip. However, it is uncertain whether frictional heating of short duration can induce changes in magnetic properties, and by how much magnetic susceptibility might increase during high-velocity slip.

Nakamura et al. [2002] and Fukuchi et al. [2005] discussed the effect of frictional melting on magnetic properties based on the results of high-velocity frictional tests using ilmenite-series granite and natural fault gouges from the Nojima fault, which ruptured in the 1995 Kobe earthquake. They succeeded in producing microstructures and magnetic properties similar to those of natural pseudotachylyte within the Nojima fault. However, changes in magnetic properties resulting from high-velocity frictional behavior have not been reported for the Chelungpu fault gouge, which is of Chinshui shale origin and thus different from Nojima fault gouge derived from Nojima Granite.

Therefore, we carried out high-velocity frictional tests using crushed gouge of Chinshui shale to allow us to compare gouge samples before and after high-velocity shear. We measured magnetic susceptibility and carried out grain-size and thermomagnetic analyses before and after the slip tests. Thermomagnetic analysis can detect possible magnetic changes caused by temperature increases. The comparison of gouge samples before and after high-velocity shear allowed us to investigate the cause of high magnetic susceptibility in the Chelungpu fault.

2. Sample Preparation and Experimental Method

Weakly deformed siltstones in Hole B at 1134 m depth, 2.5 m above the FZB1136 fault zone, were chosen for high-velocity frictional tests. A local geothermal anomaly observed within FZB1136 suggests that it is a candidate for the slip zone of the 1999 Chi-Chi earthquake [Kano et al., 2006]. To simulate gouge material, the siltstone samples were roughly crushed with an agate mortar and pestle and sieved to retain only grains of less than 0.15 mm diameter. X-ray diffraction analysis showed that this material was mostly quartz with a matrix of mainly clay minerals, such as illite, kaolinite, smectite, and chlorite.

Friction tests were performed on the gouge samples by using the high-speed rotary-shear testing apparatus of Shimamoto and Tsutsumi [1994] and the methodology of Mizoguchi et al. [2007]. A 1-g sample of gouge was placed between a pair of calcite-cemented quartz rich sandstone cylinders from Australia (0.2 mm of average grain size, 10 % of porosity, 10^{-17} m^2 of permeability) of about 25 mm diameter, of which the rough end surfaces had been smoothed by grinding with #80 silicon carbide powder (Fig. 1a). The samples were oven dried at 80 °C before the experiment, though they were exposed to a humid environment during the experiment. A gouge layer of about 1 mm thickness was shared by rotating the one of the cylinders. A Teflon sleeve was used to cover the simulated fault plane so that the gouge was confined between the sandstone surfaces during shearing. 1500 RPM of constant rotational speed was used for all tests. Slip rate varies within the apparatus as a function of distance from the center of the axis of rotation; slip displacement and rate are zero at the center of sample and largest at the edge of the sample. Slip velocity is 1.96 m/s at the edge in our test condition. Magnetic analyses were carried out several days after frictional tests. For magnetic analysis, we thus divided the shear plane into several annuli of equal width. Bulk magnetic susceptibility was measured at Kochi University using a Kappabridge KLY-3S sensor. Thermomagnetic analyses were carried out with a Natsuhara Giken NMB-89 thermobalance at Kochi University. Crushed bulk samples were heated to 600 °C and then cooled to room temperature at a rate of 6 °C/min in air with a magnetic field of 0.4 T at atmospheric pressure. Changes in the induced magnetization were monitored at 1-s intervals. Simple heating tests, which samples were heated to target temperatures from 300 to 600 °C by a commercial oven at a rate of 50 °C/min in air condition, were also carried out to measure bulk magnetic susceptibility.

Grain-size distributions of crushed gouge samples were measured by the laser diffraction and scattering method using a commercial particle-size analyzer (Mastersizer 2000, Malvern Instruments Ltd.). This apparatus can simultaneously measure a broad range of grain sizes from 0.02 to 2000 μm for an incohesive sample of only 0.1 g. Thus it was suitable for the incohesive rocks and limited samples sizes of our experiments.

3. Results

3.1. High-Velocity Rotary Shearing Test

High-velocity rotation (HVR) tests were performed at low normal stress from 0.5 to 1.5 MPa. Friction increased rapidly at the beginning of slip, then decreased gradually to reach a stable level. Peak values of the coefficient of friction were in a range of about 0.8 to 1.2, and they stabilized at around 0.2 (Fig. 1b). These results are similar to those of HVR experiments on Nojima fault gouges reported by Mizoguchi et al. [2007]. After the experiment, the color of the surface of the crushed gouge had changed to a dark gray or black, and it became darker as the distance from the axis of the apparatus increased. Under microscopic examination, the surface of the gouge was clearly slickensided, with striations oriented parallel to the slip direction (Fig. 1c). This implies that the gouge had slipped at its boundary with the sandstone block. Foliations were also formed within the gouge zone (Fig. 1d). Grains smaller than 1 μm were generally identifiable; no grains had been plastically elongated, and hourglass structures or glass-supported structures were not observed.

3.2. Magnetic Properties

Bulk magnetic susceptibility was plotted as a function of the frictional work converted to heat on the slip surface (Fig. 2a). Frictional work was determined from the relationship between shear stress and average slip displacement for each test (Fig. 2b). The initial magnetic susceptibility was 300 (μSI units on a volume basis), and increased as frictional work increased. When magnetic susceptibilities were compared for different parts of the same HVR sample, marginal parts showed higher magnetic susceptibilities than central parts. The highest magnetic susceptibility was recorded from the marginal part of sample HVR 921 (10400 μSI), which is 30 times the initial value. We plotted the magnetic susceptibility for simple heating tests from 300 to 600 °C in the same figure. The highest magnetic susceptibility of 1390 μSI was observed at 500 °C, which is smaller than that for most of the HVR samples.

Thermomagnetic curves (Fig. 3) of the HVR samples before and after shearing in the central and middle parts of the fault plane were smooth at low temperatures, but deviated from this trend at about 400 °C. Induced magnetization during heating began to increase at about 400 °C, reached a maximum at about 480 °C, and then decreased from 480 to 600 °C. During the cooling phase, induced magnetization increased smoothly, but remained lower than the level throughout the heating phase. In contrast, the thermomagnetic curves for samples from the marginal part of the fault plane showed little fluctuation from the smooth trend above 400 °C during heating. All samples showed no fluctuations from the smooth trend during the cooling phase.

3.3. Grain Size

The grain-size distributions of samples before and after shearing are shown in Figure 4. In general, the grain size of the gouge after shearing was smaller, although some large grain fragments of around 0.1 to 1 mm diameter were formed by the shearing process. The formation of new large fragments is more marked in samples from the marginal part of the fault plane. However, overall changes in the grain-size distribution after shearing were small.

4. Discussion

Most previous studies have considered the relationship between fault-related pseudotachylyte and its high initial magnetic susceptibility [e.g., Ferré et al., 2005]. Our experiments succeeded in producing ultracataclasite with high magnetic susceptibilities without forming pseudotachylyte. Our experimental results support the assumption that heat generation of short duration, even if it is below the melting point, can increase magnetic susceptibility. Further, that fault gouge derived from siltstone can show high magnetic susceptibility due to frictional heating supports the assumption of Hirono et al. [2006b] that frictional heating was responsible for the magnetic susceptibility anomaly in BM disc from Hole B.

Magnetic susceptibility is strongly influenced by the concentration of ferrimagnetic minerals such as magnetite and hematite, and by the grain size of those ferrimagnetic minerals [e.g., Dearing, 1999]. Magnetic susceptibility for the HVR tested samples was proportional to frictional work, as shown in Figure 2. Frictional work is closely related to maximum generated temperature and the duration of heat exposure for gouge samples. However, small increase of magnetic susceptibility for simple heating sample indicates that frictional heating alone cannot account for the huge increase of magnetic susceptibility for HVR sample. It has been reported that mechanochemical treatments using a planetary ball mill can transform the magnetic materials [Zdujić et al. 1998]. Therefore both thermally and mechanically driven mineral transformations must contribute to the anomalous high susceptibilities.

The magnetic susceptibility of the BM disc [Hirono et al., 2006b] was about twice that of the surrounding fault breccias and country rock, but the anomalous value was far smaller than the magnetic susceptibilities of our experimental gouges. The decrease in grain size of our sheared samples (Fig. 4) might have enhanced the increase in magnetic susceptibility, although this effect was not observed in TCDP core samples studied by Mishima et al. [2006]. However, magnetic susceptibility is mostly dependent on grain size in the superparamagnetic size range (<0.03 mm for magnetite), and we did not detect changes in grains as small as this. Moreover, the experimental gouge was rich in clay minerals, so it would be difficult to further decrease the grain size of magnetic minerals by shearing [Fukuchi et al., 2005]. The difference of the magnetic susceptibility of BM disc from that of the artificial gouge can be explained by the low resolution of the TCDP data of Hirono et al. [2006b], which were measured with a Bartington MS2E surface sensor. If the Chelungpu fault was locally sheared within a very thin slip zone, we might have underestimated bulk magnetic susceptibility in the zone of heat generation. However it is also plausible that amount of transformation of paramagnetic minerals to hematite at temperatures exceeded 480 °C is larger in the natural fault, since hematite is weakly ferromagnetic.

The deviations observed on the thermomagnetic curves (Fig. 3) can be interpreted to be the effect of thermal decomposition of siderite [Pan et al., 2000], lepidocrosite [Özdemir and Dunlop, 1993], or ferrimagnetic iron sulfide [Snowball and Torii, 1999] to form magnetite or maghemite. The characteristic deviations of the thermomagnetic curve for the initial sample and the sheared samples from the central part of the simulated fault plane were also observed for the gray and black gouge of Hole B samples [Mishima et al., 2006]. Therefore, these gouge materials might include thermally unstable iron-bearing minerals that can be transformed to magnetite or maghemite at temperatures above 400 °C. In contrast, the thermomagnetic curves of samples from the marginal part of the simulated fault plane showed no significant deviation above 400 °C; these are the characteristics the thermomagnetic curves of the BM disc material.

Therefore, the marginal part of the fault plane likely reached temperatures of at least 400 °C because of frictional heating, but without reaching melting point.

5. Summary

Our high-velocity frictional tests produced a simulated cataclasite with high magnetic susceptibility similar to that from within the Chelungpu fault zone. Our result indicates that even short duration heating due to frictional slip without the formation of pseudotachylyte can have caused the anomalous magnetic properties observed. The high magnetic susceptibility in HVR tested samples can be explained by the formation of magnetic minerals by thermal decomposition and by mechanochemical reaction during high-velocity friction. Our result confirms the high magnetic susceptibility of the Chelungpu fault slip zone is caused by earthquake slips.

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Captions

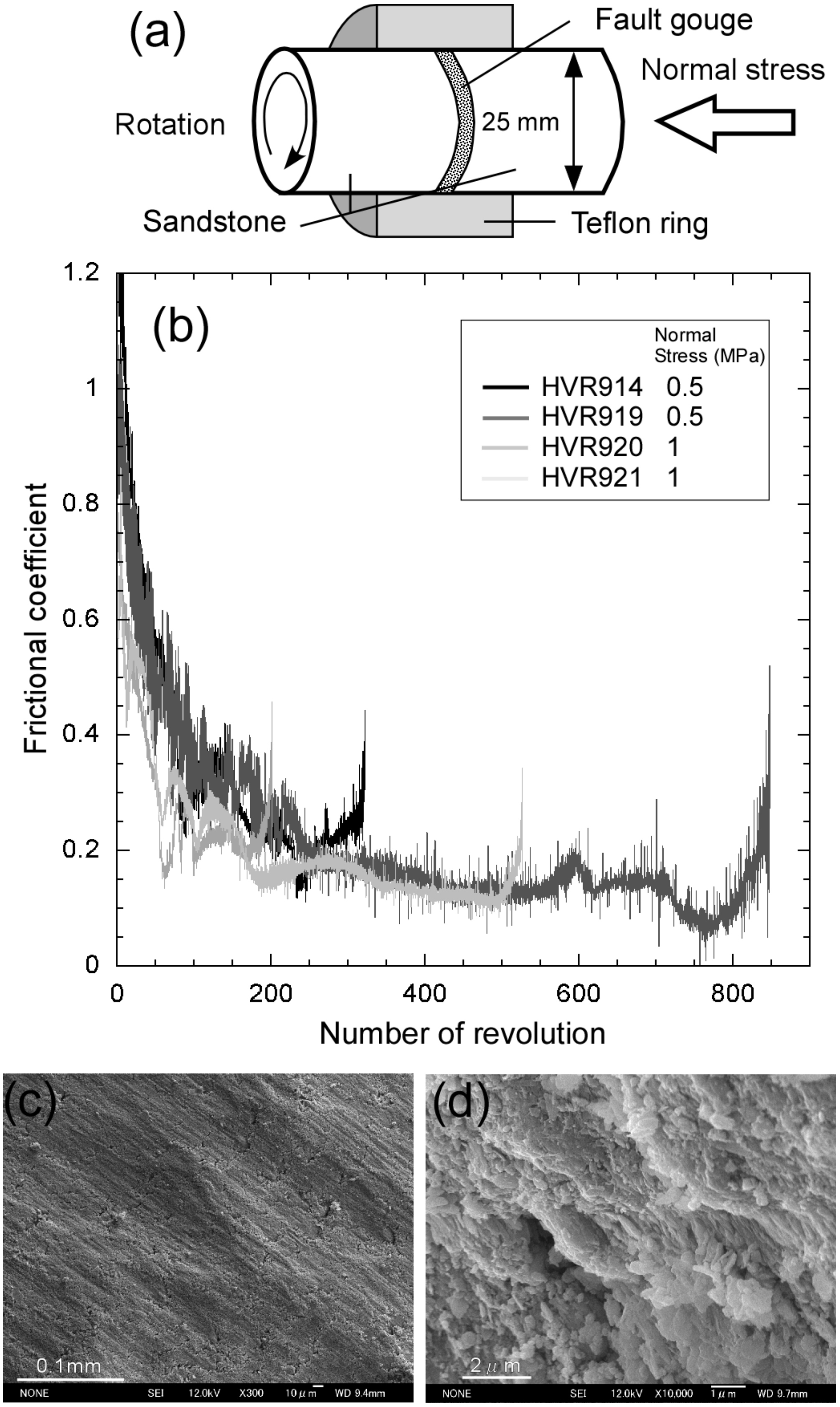
(a)
Fault gouge
Normal stress
Rotation
25 mm
Sandstone
Teflon ring
(b)
Normal Stress (MPa)
HVR914 0.5
HVR919 0.5
HVR920 1
HVR921 1
Frictional coefficient
Number of revolution
0
0.2
0.4
0.6
0.8
1
1.2
0
200
400
600
800
(c)
0.1mm
NONE SEI 12.0kV X300 10μm WD 9.4mm
(d)
2μm
NONE SEI 12.0kV X10,000 1μm WD 9.7mm

Figure 1. (a) Schematic diagram of the apparatus used for the High Velocity Rotation (HVR) test. (b) Friction as a function of slip displacement for the HVR test. (c) Slickensides on the slip surface of the crushed gouge after the HVR test. (d) Foliations formed within crushed gouge.

Figure 2

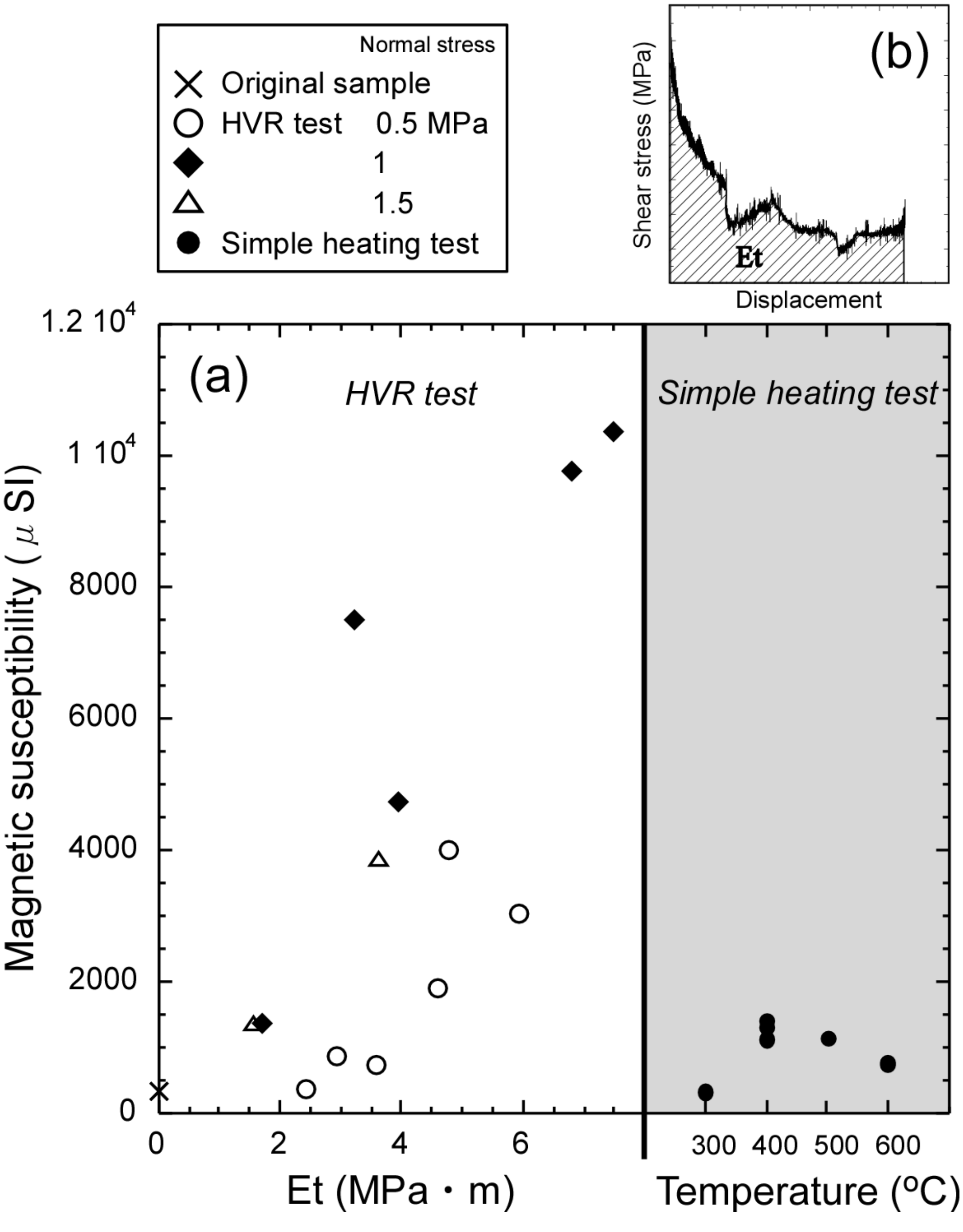

Figure 2. (a) Magnetic susceptibility for HVR test and simple heating test samples. (b) The hashed area shows the calculated frictional work.

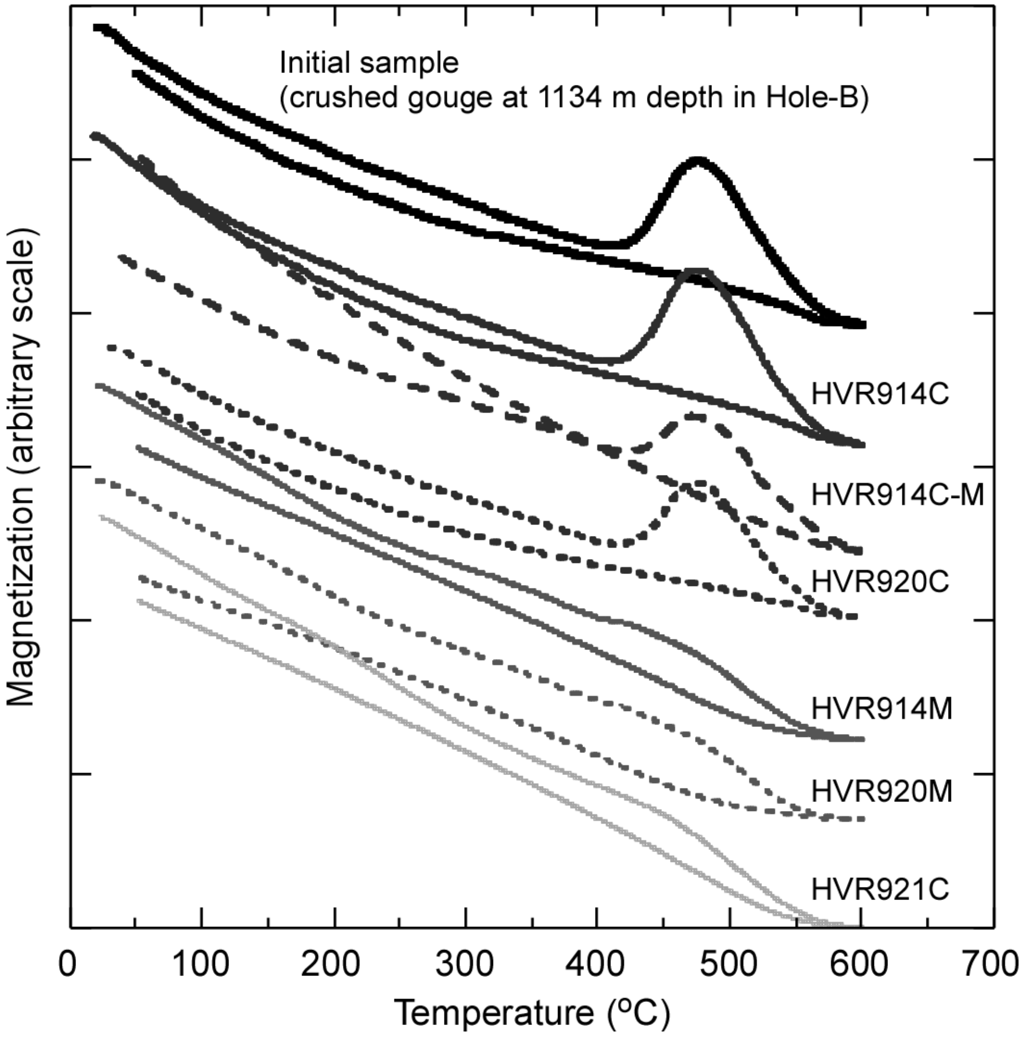

Figure 3. Thermomagnetic curves of the HVR test samples. Suffixes of sample numbers indicate the areas of the simulated fault plane from which the samples came: C, central part of simulated fault plane (0 to 6 mm from the center of the slip surface when we divided by two annuli, 0 to 4 mm when divided by three); C-M, middle part (4 to 8 mm); M: Marginal part (6 to 12 mm when divided two, 8 to 12 mm when divided three).

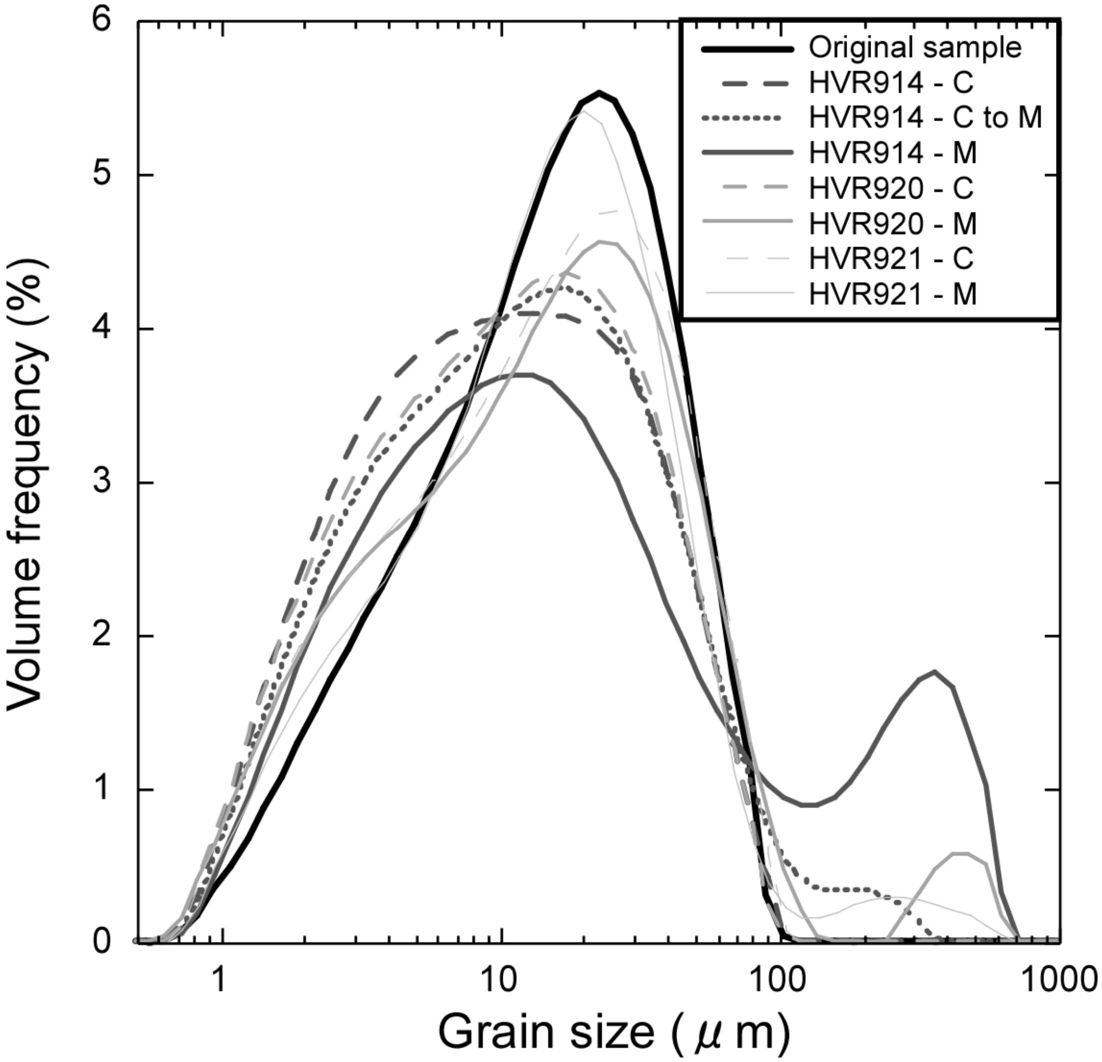

Figure 4. Grain-size distributions of HVR test samples.